Aeration Management for Stored Hard Red Winter Wheat: Simulated Impact on Rusty Grain Beetle (Coleoptera: Cucujidae) Populations

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ABSTRACT Simulation studies were conducted to determine temperature accumulations below defined thresholds and to show the impact of controlled aeration on populations of the rusty grain beetle, *Cryptolestes ferrigineus* (Stephens), a major secondary pest of stored wheat, *Triticum aestivum* (L.). Recorded data from weather stations in Texas, Oklahoma, Kansas, eastern New Mexico, and eastern Colorado (356 total) were used to determine hours of temperature accumulation below 23.9°C in June and July, 15.6°C in September and October, and 7.2°C in December. At an airflow rate of 0.0013 $m^3/s/m^3$ (0.1cubic ft ^{3}/min/bu), which requires 120 h of temperatures below the specified threshold to complete an aeration cycle, summer cooling at 23.9°C in bulk-stored wheat could be completed throughout the hard red winter wheat zone except for extreme southern Texas. An early-autumn cooling cycle at 15.6°C could not be completed throughout most of Texas and Oklahoma before the end of September. The late-autumn cooling cycle could be completed in all states except Texas by the end of November. Five geographic regions were delineated and the times required for completion of the summer, early-autumn, and late-autumn cooling cycles within each region were estimated. Population growth of the rusty grain beetle was modeled for San Antonio, TX; Abilene, TX; Tulsa, OK; Topeka KS; and Goodland, KS, by predicting the numbers of adults in the top, outer middle, outer periphery, and the center of the bin during a 1-yr storage season. Populations of *C. ferrugineus* in San Antonio and Austin were predicted to exceed the Federal Grain Inspection Service (FGIS) threshold of two beetles per kilogram of wheat in all four levels of the bin during late autumn, decline during the winter, and increase the following spring. In Midland, TX, and Oklahoma City, OK, populations were predicted to exceed the threshold only in the top and outer middle of the bin, whereas populations in the Kansas locations were not predicted to exceed the threshold at any time.

KEY WORDS *Cryptolestes ferrugineus*, rusty grain beetle, wheat, storage, aeration, modeling

HARD RED WINTER wheat, *Triticum aestivum* (L.), is grown primarily in Texas, Oklahoma, Kansas, and the high plateaus of eastern Colorado and eastern New Mexico. It is planted in midautumn and harvested from mid-May to mid-July, depending on latitude. After harvest, the wheat is usually stored on-farm or in large commercial elevators, where it can be infested by a variety of beetle species. The lesser grain borer, *Rhyzopertha dominica* (F.), and the rice weevil, *Sitophilus oryzae* (L.), are two important primary pests that undergo larval development inside the kernel. Secondary pests that develop outside the kernel, including sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.), rusty grain beetle, *Cryptolestes ferrugineus* (Stephens), the flat grain beetle, *Cryptolestes pusillus* (Schönherr), and red flour beetle, *Tribolium castaneum* (Herbst), also can cause economic damage.

The optimum temperature range for growth and development of these beetle species is ≈25–35°C, and development is greatly reduced and oviposition virtually ceases at temperatures <18.3° or >35°C (Howe 1965, Fields 1992). Although high temperatures can limit insect populations in stored wheat, infestations usually develop during the summer because grain temperatures are normally <36°C. Dowdy and McGaughey (1994) conducted a detailed survey in Kansas and found several beetle species to be abundant in farm-stored wheat and commercial facilities during the first 2 mo of storage after the wheat was harvested and binned. Reed et al. (1991) also found lesser grain borer in farm-stored wheat in Kansas. Insect pests have been detected during the summer in wheat stored in Oklahoma (Cuperus et al. 1986).

As temperatures begin to decline in autumn, stored wheat can be cooled through low-volume aeration with ambient air (Cuperus et al. 1990). In the absence of aeration, large bulks of wheat will stay warm throughout the winter (Schmidt 1955). Published guidelines recommend an initial cooling cycle at an activation threshold of 15.6 or 18.3°C as temperatures begin to decline in September (Noyes et al. 1987). The time required to cool a storage bin depends in part on the fan speed. An airflow rate of 0.0013 $m^3/s/m^3$ (0.1 CFM/bu) is a standard recommendation for stored

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hard red winter wheat (Flinn et al. 1997), in part because power costs will increase as airflow rates increase (Kline and Converse 1961). At this airflow rate, 120 h of temperatures below a specified threshold are needed to cool a storage bin (Noyes et al. 1987). In a previous simulation study of maize weevil population development on corn stored in the southern United States (Arthur et al. 1998), airflow rates of 0.0013, 0.0026, and 0.0039 $m^3/s/m^3$, which corresponded to 0.1, 0.2, and 0.3 cubic ft ^{3}/min/bu, respectively, were used for the simulations. Although the bin cooled more quickly as the airflow rates increased, predicted maize weevil populations were usually lower in the 120-h than in either the 40- or 60-h cooling cycles. Increasing the aiflow rates and thereby decreasing the time required to complete a cooling cycle did not yield a corresponding predicted decrease in maize weevil populations.

Several recent studies have described the benefits of using automatic aeration controllers starting at harvest that activate the cooling system only when temperatures fall below specified thresholds, versus manual aeration in which the fans are constantly in operation until turned off (Reed and Harner 1998a, Flinn et al. 1997). Fan controllers that efficiently cool grain are not necessarily new, but historically they have been used more for moisture control than for insect control, and were more complex and costly than the simple controllers that are now being recommended (Hagstrum et al. 1999). Several studies have indicated that early aeration immediately after harvest may suppress insect pest populations (Reed and Harner 1998b). Flinn et al. (1997) conducted a modeling study simulating aeration cooling when outside temperatures were at least 10°C below grain temperatures and showed that automatic cooling starting at harvest reduced rusty grain beetle populations compared with automatic cooling starting 1 September. Temperature data from three locations were used to drive the simulations: Tulsa, OK; Topeka, KS; and Sioux Falls, SD

Detailed temperature information for the hard red winter wheat belt would be necessary to develop aeration management strategies for specific climatic regions within this broad area. Also, it would be more practical to design aeration strategies that use inexpensive automatic controllers. These controllers cost approximately \$200-\$300, and are being recommended by extension specialists who work with stored wheat (Reed et al. 1993, Noyes et al. 1995). The controllers will record the numbers of hours that the aeration fans are operating, and after a cooling cycle is completed for a given fan speed, the controller is manually set to the next lower temperature threshold.

Modeling studies were conducted by simulating a summer aeration cycle after harvest in addition to the standard early-autumn and late-autumn cooling cycles. Specified activation temperatures chosen for the model simulations were 23.9°C (75°F) for summer cooling, 15.6°C (60°F) for the early-autumn cooling, and 7.2°C (45°F) for the late-autumn cooling. The airflow rate specified for the simulations was 0.0013 $m^3/s/m^3$ (0.1 CFM/bu), which was selected to conform to standard recommendations and practical use. The four objectives of this study were as follows: (1) to estimate hours of temperature accumulations below threshold temperatures of 23.9°C during June and July, 15.6°C during September and October, and 7.5°C during November and December; (2) use data from selected weather stations to subdivide the hard red winter wheat region into different zones representing climatic variation in wheat storage conditions; (3) within each zone, estimate dates by which an aeration cooling cycle of 120 h (which corresponds to an airflow rate of 0.0013 $m^3/s/m^3$) could be completed during the summer, early autumn, and late autumn; and (4) simulate bin cooling and population growth of the rusty grain beetle, based on hourly weather data for five selected weather stations. The rusty grain beetle was selected for the modeling studies because it is the predominant species found in stored hard red winter wheat (Hagstrum 1987).

Materials and Methods

Temperature Model. Recorded daily high and low temperatures for various weather stations in Texas, Oklahoma, Kansas, New Mexico, and Colorado were obtained on CD-ROM from Earth Info (Boulder, CO). Stations within a state were selected based on 95% coverage of data points between the years 1960 and 1989. Stations in New Mexico and Colorado were eliminated if they were west of 104.5° W longitude because little wheat is grown in the mountain regions. The final number of stations used in the study were 147 in Texas, 77 in Oklahoma, 96 in Kansas, 19 in New Mexico, and 17 in Colorado (356 total). Daily sunrise and sunset at each station were estimated with a model that calculates daily sunrise and daily sunset based on latitude, longitude, and time zone. The 30-yr temperature data were averaged into a data set with the means procedure of the statistical analysis system (SAS Institute 1987).

A model previously described in detail (Arthur and Johnson 1995) that calculates hourly temperature based on the daily high and low temperature, sunrise, and sunset was used to estimate temperature accumulations at each station below specified thresholds: 23.9°C (75°F) during June and July, 15.6°C (60°F) during September and October, and 7.5°C (45°F) during November and December, using the 30-yr average data set created for the years 1960–1989. Data for each station were then used to develop contour lines for temperature accumulations during the three time periods with Surfer software (Golden Software, Golden, CO). These contour lines were then incorporated into maps with MapInfo software (Mapinfo, Ithaca, NY).

Eighteen airport weather stations with complete hourly meteorological data available on Samson CD-ROM from the National Climatic Center (Asheville, NC) were grouped into five zones based on the total number of hours from 1 September to 31 October in which the temperature was ≤15.6°C. This temperature is a realistic activation temperature for autumn

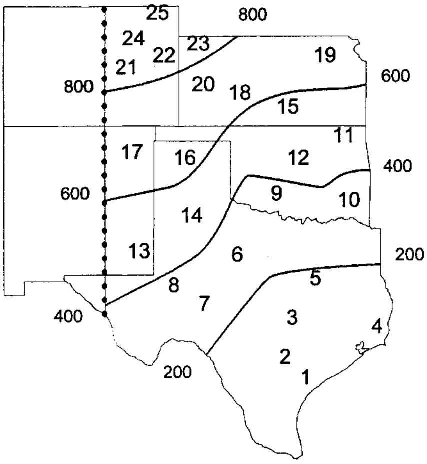

Fig. 1. Delineation of five zones based on total hours at <15.6°C from 1 September to 31 October: zone 1, 1–200 h; zone 2, 201–400 h; zone 3, 401–600 h; zone 4, 601–800 h; and zone 5, >800 h. The numbers represent the approximate locations of the weather stations listed in Table 1.

aeration of hard red winter wheat, and accumulation studies have been conducted with 1 September as a starting date (Noyes et al. 1987). These five zones were as follows: (1) 1–200 h, (2) 201–400 h, (3) 401–600 h, (4) 601–800 h, and (5) >800 h (Fig. 1). Additional weather stations were added to give at least five weather stations for each zone.

Average dates for wheat binning after harvest, based on summarized statistical data for each state, were estimated to be 31 May for zone 1, 7 June for zone 2, 14 June for zone 3, 21 June for zone 4, and 28 June for zone 5. The dates by which 120 h were accumulated below threshold temperatures of 23.9°C for each station were estimated by starting the accumulations for the summer aeration cycle with the binning date. The completion dates for the early-autumn aeration cycle were estimated by starting the accumulations on 1 September for the same number of hours <15.6°C. The completion dates for the late-autumn cooling cycle at 7.2°C were estimated starting with an accumulation date of 1 November.

Insect Population Model. Five airport weather stations that were in the approximate midpoint of each geographic region were selected for model simulation studies. These stations were San Antonio, TX; Abilene, TX; Tulsa, OK; Topeka, KS; and Goodland, KS. The 30-yr hourly weather data for each year from 1960 to 1989 for the five weather stations were summarized into a 2-yr file that contained the averaged hourly temperature for each date. The spatial model used in this study was previously described by Flinn et al. (1997). It uses a two-dimensional representation of a steel grain bin, starting from the bin center and proceeding to the bin wall. The simulated bin holds 272.2 tons of wheat (10,000 bu) and is divided mathematically into 16 regions. The bin diameter was 7.54 m. The model predicts rusty grain beetle population dynamics in each of the regions based on temperatures and

Table 1. Listing of weather stations grouped into five zones based on the number of hours below 15.6°C from 1 September to 31 October: zone 1, 1–200 h; zone 2, 201–400 h; zone 3, 401–600 h; zone 4, 601–800 h; and zone 5, >800 h

Zone	Binning date	ID no.	Station	Latitude	Longitude	Total hours
1	31 May	1	Victoria, TX	28′ 51°	96′ 55°	29
		2	San Antonio, TX	29′ 32°	98′ 28°	68
		3	Austin, TX	30′ 17°	97′ 42°	69
		4	Port Arthur, TX	29′ 57°	94′ 01°	70
		5	Waco, TX	31′ 37°	97′ 13°	147
2	7 June	6	Abilene, TX	32′ 25°	99′ 41°	258
		7	San Angelo, TX	31′ 32°	100′ 30°	271
		8	Midland, TX	31′ 57°	102′ 11°	346
		9	Altus, OK[a]	34′ 58°	99′ 33°	377
		10	Durant, OK[a]	34′ 22°	96′ 38°	390
3	14 June	11	Tulsa, OK	36′ 12°	95′ 54°	420
		12	Oklahoma City, OK	35′ 21°	97′ 36°	422
		13	Hobbs, NM[a]	32′ 42°	103′ 08°	473
		14	Lubbock, TX	33′ 39°	101′ 49°	497
		15	Wichita, KS	37′ 39°	97′ 26°	566
4	21 June	16	Amarillo, TX	35′ 14°	101′ 42°	607
		17	Tucumcari, NM	35′ 12°	103′ 41°	623
		18	Dodge City, KS	37′ 46°	99′ 58°	635
		19	Topeka, KS	39′ 04°	95′ 38°	677
		20	Syracuse, KS[a]	37′ 59°	101′ 45°	733
5	28 June	21	Pueblo, CO	38′ 17°	104′ 31°	820
		22	Burlington, CO[a]	39′ 18°	102′ 16°	858
		23	Goodland, KS	39′ 22°	101′ 42°	862
		24	Byers, CO[a]	39′ 45°	104′ 08°	942
		25	Sterling, CO[a]	40′ 37°	103′ 13°	948

[a] These stations were not primary airport weather stations, but were included to provide five stations for each zone.

moistures predicted by the bin temperature model (Metzger and Muir 1983). The insect model uses a distributed delay with 0.1-d intervals to predict insect population growth of all stages, and includes density-dependent and cold-temperature mortality. The immigration rate of rusty grain beetles into the bins was arbitrarily set at 40 adults per 27.2 tons/d in the top two layers and 20 adults per 27.2 tons/d in the bottom two layers (Flinn et al. 1997), and immigration ceased on 1 October. The bin temperature model uses hourly meteorological data for wet- and dry-bulb temperature, wind speed, and cloud opacity to predict changes in grain temperature and moisture. The model includes both conduction and convective modes of heat exchange. Thus, cooling or warming of the grain with aeration fans can be simulated as well as no aeration. The model also simulates changes in grain moisture caused by aeration. In the simulations, push aeration at an airflow rate of 0.0013 $m^3/s/m^3$ (0.1 $foot^3/min/bu$) was specified, the model assumed a 1.3°C temperature rise caused by heat of compression by the fan, and the bin floor was fully perforated to obtain uniform airflow through the grain.

The 30-yr hourly weather data from 1960 to 1989 for the five weather stations were summarized into a 2-yr file that contained the averaged hourly temperature for each date. Binning was simulated on 31 May, 7 June, 14 June, 21 June, and 28 June for zones 1–5, respectively. Simulations were run from binning until 30 May the next year. The initial grain temperature was 36.2°C and moisture content was 12%. In the simulations, no aeration was compared with semiautomatic aeration starting at harvest. Semiautomatic aeration was modeled with a simulated air-temperature sensor and fan hour-meter. Operation of the fan and forced aeration of the grain was simulated when the outside air temperature was less than the air temperature set point. Three temperature set points, 23.9, 15.6, and 7.2°C, were selected to simulate summer, early-autumn, and late-autumn cooling, respectively. The initial set point was 23.9°C. After the fan hour-meter accumulated 120 h, the set point was switched to 15.6°C. After 120 h were accumulated again, it was set to 7.2°C. The fan controller was turned off after 120 h accumulated at the lowest set point. One hundred and twenty hours of fan run-time was used because this is the number of hours it takes for a cooling front to pass through the grain at the selected airflow rate. The fan was operated intermittently rather than continuously. When the fan was on, the model simulated the exchange of heat and moisture between the grain layers and the aeration air. When the fan was off, heat conduction through the grain bulk in the vertical and radial directions was simulated. Because push aeration was simulated, cool air starts at the bottom of the grain mass and gradually moves to the top of the grain mass.

Results

One hundred and twenty hours of temperatures <23.9°C in June and July was required to complete a summer cooling cycle at a fan speed of 0.0013 $m^3/s/m^3$ (0.1 $foot^3/min/bu$), which could be accomplished in most of the hard red winter wheat zone except for extreme southern Texas (Fig. 2). The hours in which the temperatures are <23.9°C will probably occur mainly at night, especially in the southern regions, and the automatic controllers can be set to operate only when ambient temperatures drop <23.9°C. Constant manual aeration would not be practical for summer cooling because the wheat would obviously rewarm during the day if the fans were not turned off. Manual aeration would require an operator to monitor temperatures and prevent the fans from running when the temperature threshold is exceeded.

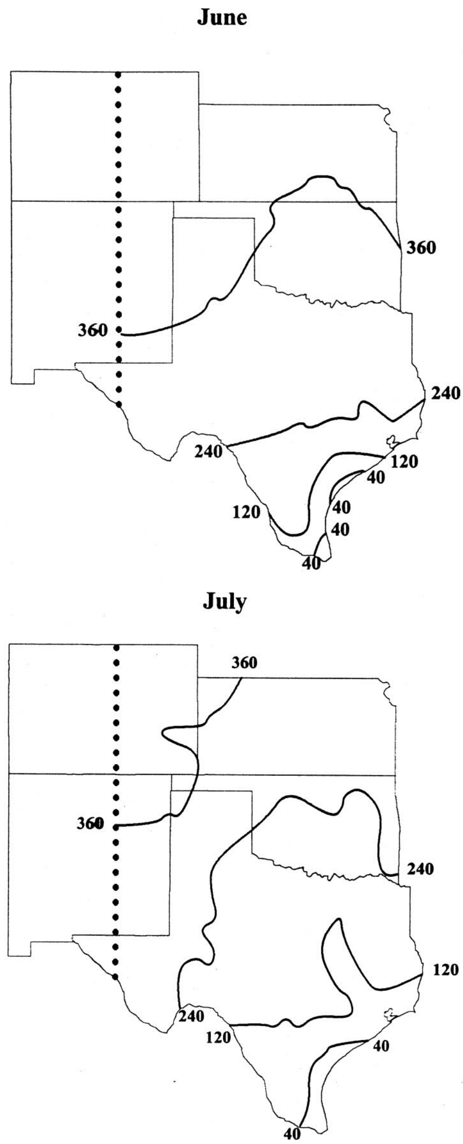

Fig. 2. Total number of hours at <23.9°C in the hard red winter wheat region during June and July.

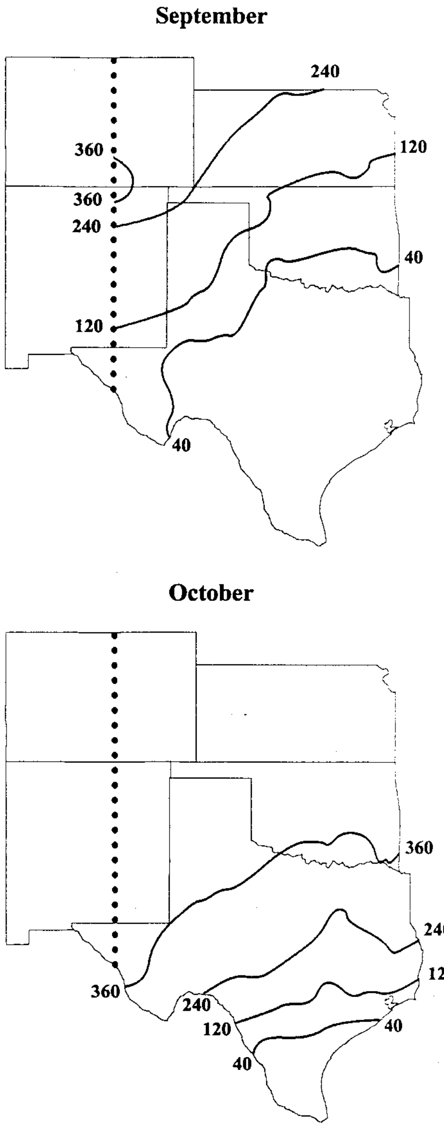

Fig. 3. Total number of hours at <15.6°C in the hard red winter wheat region during September and October.

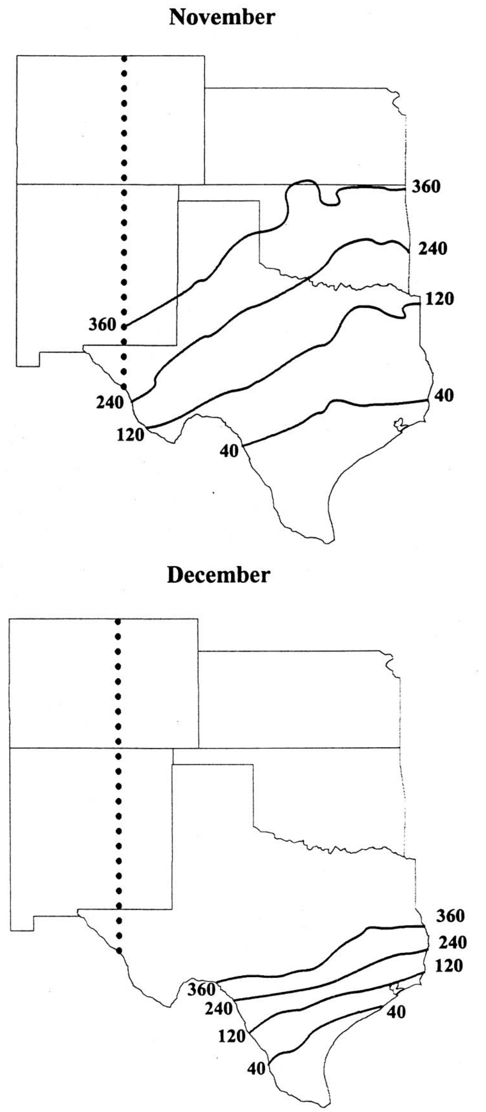

Fig. 4. Total number of hours at <7.2°C in the hard red winter wheat region during November and December.

Temperatures in Texas and Oklahoma are not normally cool enough to complete an early-autumn cooling cycle at 15.6°C in September; however, the cycle could be completed by the end of October in both states, with the exception southern Texas (Fig. 3). The cooling cycle could be completed by the end of September in Kansas and eastern Colorado, but temperatures during much of September will be in the range of 25–35°C, which will support the rapid growth and development of insect pest populations. A third cooling cycle of 7.2°C could be completed in all states except Texas by the end of November (Fig. 4). Temperatures inside the bins should already be cool enough to inhibit population growth. The summer cooling cycle was completed within 18 d of binning in all five zones (Table 2). The times required to complete the early-autumn and late-autumn cooling cycles are more dependent on regional climate than is the summer cycle, and cooling cycles for both the early-autumn and the late-autumn activation temperatures were completed at earlier calendar dates as the zones move from south to north.

Simulation results with the insect model showed that automatic aeration may not completely suppress rusty grain beetles in Texas, and chemical fumigations during the storage season may be required to reduce populations below the economic threshold. The model predicted that populations would be well above the economic threshold of two or more insects per kilogram in Austin, TX, the warmest location, in all

Table 2. Average calendar date, averaged to the nearest whole number, ± SE in days, by which the summer (23.9°C), early-autumn (15.6°C), and late autumn (7.2°C) cooling cycles are completed for the stations listed in Table 1

Zone	Summer	Early-autumn	Late-autumn
1	06/16 ± 2 (16)	11/05 ± 2 (65)	12/21 ± 5 (50)
2	06/19 ± 0 (12)	10/16 ± 2 (45)	11/26 ± 2 (26)
3	06/26 ± 1 (12)	10/06 ± 1 (35)	11/16 ± 1 (16)
4	07/02 ± 1 (11)	09/25 ± 1 (25)	11/10 ± 1 (10)
5	07/08 ± 1 (10)	09/14 ± 1 (14)	11/08 ± 1 (8)

Accumulation dates for the summer cycle begin with the binning date, which was 31 May, 7 June, 14 June, 21 June, and 28 June for zones 1–5, respectively. The accumulation dates for the early-autumn and late autumn cycles are 1 September and 1 November (actual number of days from the starting dates are in parentheses).

four layers within the grain mass (Fig. 5). Beetle populations would be greatest in the top and outer middle layers of the bin. Predicted grain temperature in the top layer cooled slightly with the initial summer aeration, but then warmed and remained >27°C until mid-November (Fig. 5). The other layers remained at 25–27°C during the summer. The second cooling cycle in mid-November reduced temperatures to 20–22°C, whereas the third cooling cycle reduced temperatures to 12–15°C. However, this cycle was not completed until mid-January. Populations were predicted to decline during the winter but would increase in the spring to levels exceeding the threshold.

Although populations of rusty grain beetles were lower in Midland, TX, compared with Austin, TX, the patterns of growth and development were similar to predictions for Austin (Fig. 6). Maximum population levels in the top and outer middle layers were ≈3.1 and 6.8 adults per kilogram, respectively, and these peaks occurred in mid-November. The top layer cooled initially, then warmed to 30°C, whereas the other layers remained at 27 or 28°C during the summer. The third cooling cycle in December reduced temperatures in each grain level to 14 or 15°C. Both the autumn and winter cooling cycles were completed ≈1 mo earlier in Midland compared with Austin. Predictions for beetle populations in the outer periphery and the center of the bin were below the threshold; however, populations in the top and outer middle layers increased in the spring to levels exceeding the threshold.

Rusty grain beetle populations were predicted to exceed the economic threshold only in the top and middle layers of grain for the Oklahoma City location (Fig. 7); however, populations were lower than were predicted for the Texas sites. The second and third cooling cycles occurred in early October and mid-November, respectively. Predicted populations in the spring did not exceed the threshold. Predicted populations for Topeka, KS (Fig. 8), and Goodland, KS (Fig. 9), did not exceed the threshold in any layer.

Grain temperatures were predicted to be warmer for longer periods in the more southern locations compared with Kansas, which accounts for the higher population densities in the south. Also, rusty grain beetles were predicted to exceed the threshold in the

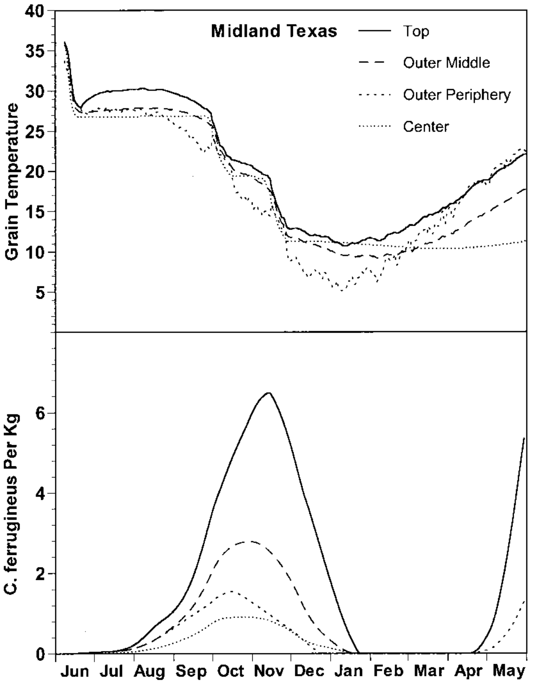

Fig. 6. Predicted grain temperatures and *C. ferrugineus* populations in the top, outer middle, outer periphery, and middle portions of wheat stored in a 272,727-kg (10,000-bu) bin in Midland, TX.

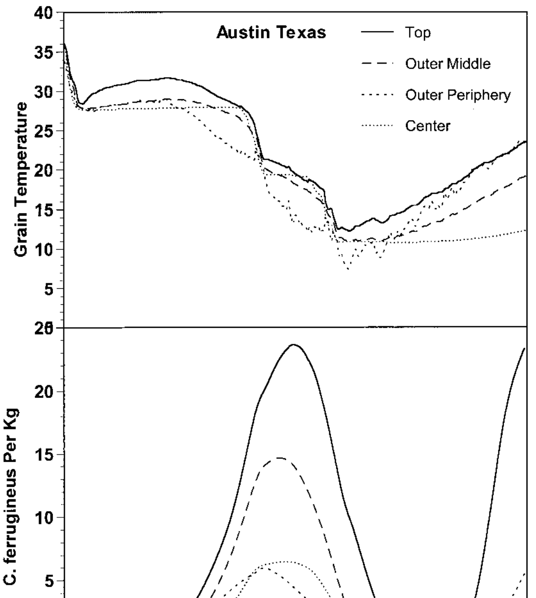

Fig. 5. Predicted grain temperatures and *C. ferrugineus* populations in the top, outer middle, outer periphery, and middle portions of wheat stored in a 272,727-kg (10,000-bu) bin in Austin, TX.

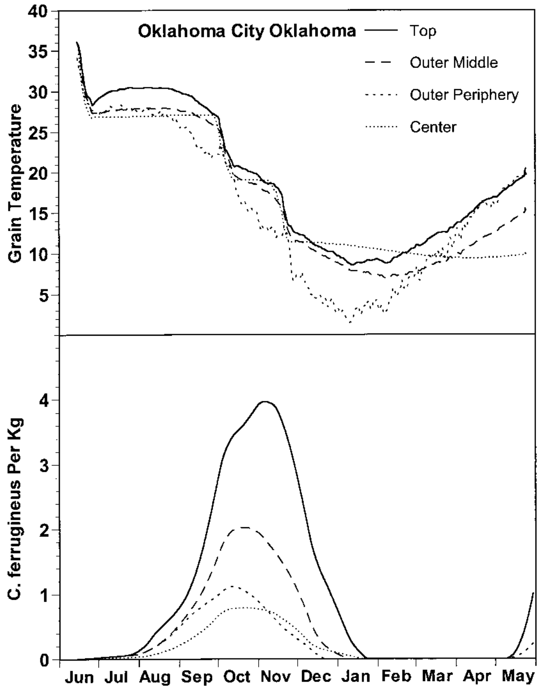

Fig. 7. Predicted grain temperatures and *C. ferrugineus* populations in the top, outer middle, outer periphery, and middle portions of wheat stored in a 272,727-kg (10,000-bu) bin in Oklahoma City, OK.

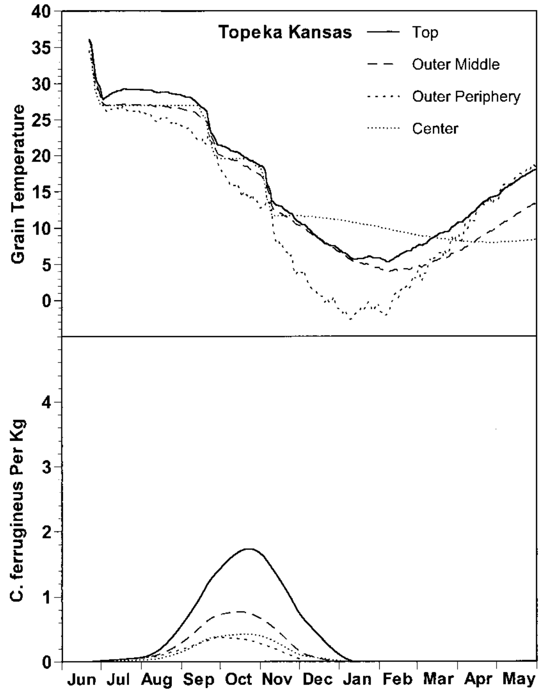

Fig. 8. Predicted grain temperatures and *C. ferrugineus* populations in the top, outer middle, outer periphery, and middle portions of wheat stored in a 272,727-kg (10,000-bu) bin in Topeka, KS.

spring of the following year in Texas as the grain warmed. The time between the first and second aeration cycles was longer in the southern locations than in the northern locations, probably because the grain was stored earlier in the southern locations and could not be cooled below the second threshold of 15.6°C until later in autumn. Also, the calendar dates at which all three cycles are completed occur later in the year in the southern than in the northern locations (1 January for Midland versus 1 November in Goodland).

Discussion

Summer aeration with automatic aeration controllers would be effective in suppressing rusty grain beetles throughout the hard red winter wheat region, except for southern Texas. Several studies recommend waiting until September for initial cooling at 12–15°C (Storey et al. 1979, Noyes et al. 1987, Cuperus et al. 1990), partly because of the belief that high harvest temperatures will inhibit insect population growth (Noyes et al. 1987). However, several field-sampling studies have shown that insect pests can be found in stored wheat during the summer (Cuperus et al. 1986, Reed et al. 1991, Dowdy and McGaughey 1994). Modeling research by Flinn et al. (1997) has shown that insect populations in South Dakota, Kansas, and Oklahoma can be suppressed below economic levels with automatic aeration controllers starting at harvest. They also showed that starting the aeration controller at harvest, rather than waiting until autumn, was more effective in cooling the grain and preventing insect infestation. In field studies, Reed and Harner (1998a) showed that automatic aeration, starting at harvest, resulted in good insect control in wheat stored in Kansas. If summer cooling is not used and infestations develop during the summer, these infestations may have to be eliminated, usually by a fumigation treatment with phosphine.

The question of extreme years and patterns often arises when interpreting the results of modeling studies based on historical weather data, particularly those studies involving field crop insects. These insects are subject to large fluctuations in ambient temperature, and variations in weather patterns during the growing season could have important consequences for insect population development. However, stored-grain insects such as the rusty grain beetle are often insulated from the effects of temperatures by the moderating effects of the grain mass (Subramanyam et al. 1991). Longstaff and Banks (1987) conducted simulation studies of heat transfer at depths of 0.025–1 m within a grain mass, and compared results of predictive equations to actual temperatures. They described three zones with distinct temperature patterns; the pattern at the surface (0.025 m) where small changes in temperatures were noticeable and reflected patterns of variation in ambient temperature, an intermediate zone at 0.1 m with reduced temperature variation and a lag compared with changes at the surface, and the

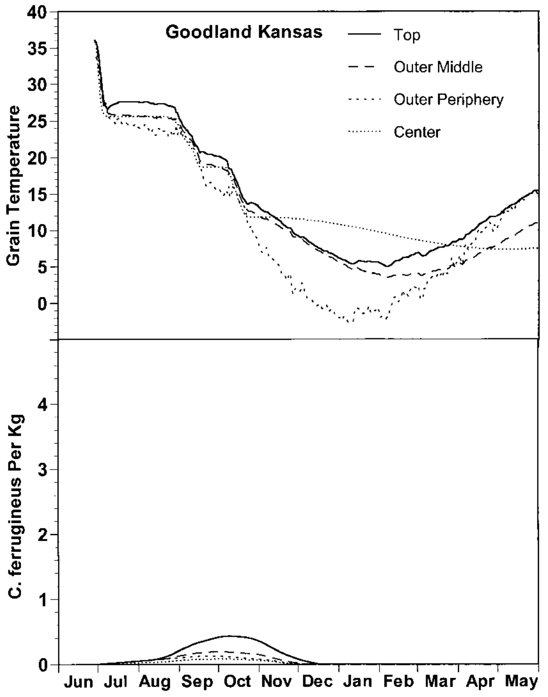

Fig. 9. Predicted grain temperatures and *C. ferrugineus* populations in the top, outer middle, outer periphery, and middle portions of wheat stored in a 272,727-kg (10,000-bu) bin in Goodland, KS.

deepest zone at 0.4 m where temperature slowly changes with little diurnal variation. This latter zone at 0.4 m would be representative of the majority of the grain mass within a bin. Once the grain is cooled through aeration, day-to-day variations in temperature would have little effect on grain temperatures, and therefore extreme temperatures could actually have very little effect on insect population development within the grain mass.

Kawamoto et al. (1992) described a process for developing regional models to estimate the potential risk of insect infestations within a given geographical area. Such models could be based on average meteorological data for 30–40 yr or data for selected years (Kawamoto et al. 1991). In our simulations we used 30 yr of daily temperature data for each of 356 weather stations for the temperature accumulation study, and 30 yr of hourly data for each of the five stations used for the insect population simulations. We described the process of temperature accumulation and aeration cycles so that results would be applicable over the broad geographic region where hard red winter wheat is stored after harvest, and to provide practical information that could be used to help manage the rusty grain beetle, a major insect pest of hard red winter wheat. In actual practice it is often impossible to determine if a current storage year is warmer or cooler than normal compared with the average because data must be collected for the entire year and compared with other historical periods to make this determination.

Historical weather data were used earlier to predict development of rusty grain beetle on wheat stored in Topeka, KS; Oklahoma City, OK; and Souix City, SD (Flinn et al. 1997). Four individual 2-yr data sets (1983–1984, 1984–1985, 1985–1986, and 1986–1987) were constructed from hourly data for the years 1983 to 1987, simulations were conducted for each data set, and results were averaged. Although conducting simulations with a limited number of yearly data sets is one option for using climatic data in modeling studies, data for any given short period, such as 5 yr, is likely to be different from any other comparable period. This could also be a point of disagreement. In our simulations, we used 30 yr of temperature data to estimate the potential risk for the entire hard red winter wheat region. The procedures used for these simulations were identical to those used to predict temperature accumulations for corn stored in Georgia (Arthur and Johnson 1995). They were also identical to those used to predict temperature accumulation and maize weevil development at nine airflow rate-activation temperature combinations for corn stored in the southern United States (Arthur et al. 1998). In both of these studies, 30 yr of data were averaged for model simulations. The studies conducted at different airflow rates showed that the optimum was 0.0013 $m^3/s/m^3$, which is why we conducted our simulations using this rate. In addition, this rate is commonly recommended for aeration of stored hard red winter wheat.

The optimal temperature range for most stored-product beetles ranges from 25 to 35°C (Fields 1992), but under optimal conditions the developmental time of any individual species will vary, depending on temperature, moisture content, and diet (Hagstrum and Milliken 1988). However, developmental times at optimal conditions are similar for many of the common stored-grain pests. For example, at 25°C and >12% moisture content, the time required to complete development from egg to adult ranges from 35 to 40 d for the rice weevil, the lesser grain borer, the rusty grain beetle, the flat grain beetle, the red flour beetle, and the sawtoothed grain beetle (Hagstrum and Milliken 1988). Recent revisions to the FGIS regulations make no distinction between internal and external feeders, they simply define the threshold as two or more insects injurious to grain per kilogram of wheat. We selected the rusty grain beetle for simulation studies because it is the predominant stored-product species found in stored hard red winter wheat (Hagstrum 1987). Variations in fecundity and development at suboptimal temperatures will affect population growth of different stored-grain beetle species (Beckett et al. 1994), therefore results described for the simulation studies using the rusty grain beetle may not be directly transferable to other pest beetles. However, the broad patterns, the potential impact of aeration, and the increased risk for grain stored in the southern region of the hard red winter wheat zone will be similar regardless of the particular insect species.

In conclusion, the results of these temperature accumulation studies and modeling simulations show that three aeration cycles—an initial cooling at harvest— cooling in September, and a final cooling in December are possible throughout the hard red winter wheat region. Results from this and other studies emphasize the benefits of using simple automatic controllers to prevent fans from running if the temperature threshold is exceeded. Improved aeration management may reduce the need for insecticides in wheat stored either on-farm or in commercial elevators. However, specific recommendations and management plans may be dependent on latitude and local climatic conditions.

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References Cited

Arthur, F. H., and H. L. Johnson. 1995. Development of aeration plans based on weather data: a model for management of corn stored in Georgia. Am. Entomol. 41: 241–246.

Arthur, F. H., J. E. Throne, D. E. Maier, and M. D. Montross. 1998. Feasibility of aeration for management of maize weevil populations in corn stored in the southern United States: model simulations based on recorded weather data. Am. Entomol. 118–123.

Beckett, S. J., B. C. Longstaff, and D. E. Evans. 1994. A Comparison of the demography of four major stored grain Coleopteran pests and its implications for pest management, pp. 491–497. *In* E. Highley, E. J. Wright, H. J. Banks, and B. R. Champ [eds.], Proceedings of the 6th International Conference on Stored-Product Protection, vol. 1. CAB, Wallingsford, Canberra, Australia.

Cuperus, G. W., C. K. Prickett, P. D. Bloome, and J. T. Pitts. 1986. Insect populations in aerated and unaerated stored wheat in Oklahoma. J. Kans. Entomol. Soc. 59: 620–627.

Cuperus, G. W., R. T. Noyes, W. S. Fargo, B. L. Clary, D. C. Arnold, and K. Anderson. 1990. Management practices in a high-risk stored-wheat system in Oklahoma. Am. Entomol. 36: 129–134.

Dowdy, A. K., and W. H. McGaughey. 1994. Seasonal activity of stored-product insects in and around farm-stored wheat. J. Econ. Entomol. 87: 1351–1358.

Fields, P. G. 1992. The control of stored-product insects and mites with extreme temperatures. J. Stored Prod. Res. 28: 89–118.

Flinn, P. W., D. W. Hagstrum, and W. E. Muir. 1997. Effects of time of aeration, bin size, and latitude on insect populations in stored wheat: a simulation study. J. Econ. Entomol. 90: 646–651.

Hagstrum, D. W. 1987. Seasonal variation in stored wheat environment and insect populations. Environ. Entomol. 16: 77–83.

Hagstrum, D. W., and G. A. Milliken. 1988. Quantitative analysis of temperature, moisture, and diet factors affecting insect development. Ann. Entomol. Soc. Am. 81: 539–546.

Hagstrum, D. W., C. Reed, and P. Kenkel. 1999. Management of stored wheat insect pests in the USA. Integrated Pest Manage. Rev. 4: 127–142.

Howe, R. W. 1965. A summary of estimates of optimal and minimal conditions for population increase of some stored products insects. J. Stored. Prod. Res. 1: 177–184.

Kawamoto, H., R. N. Sinha, and W. E. Muir. 1991. Ecosystem modeliing to provide early warning of pest infestation of stored grain, pp. 2019–2026. *In* F. Fleurat-Lessard and P. Ducom [eds.], Proceedings of the Fifth International Working Conference on Stored Product Protection, vol. 3,Bordeaux, France.

Kawamoto, H., R. N. Sinha, and W. E. Muir. 1992. Computer simulation modelling for stored-grain management. J. Stored Prod. Res. 28: 139–145.

Kline, G. L., and H. H. Converse. 1961. Operating grain aeration systems in the hard winter wheat area. U.S. Dep. Agric. Market. Res. Rep. 480.

Longstaff, R. A., and J. H. Banks. 1987. Simulation of temperature fluctuations near the surface of grain bulks. J. Stored Prod. Res. 23: 21–30.

Metzger, J. F., and W. E. Muir. 1983. Aeration of stored wheat in the Canadian prairies. Can. Agric. Engl. 25: 127–137.

Noyes, R. T., B. L. Clary, and G. W. Cuperus. 1987. Maintaining the quality of stored wheat by aeration. Okla. State Univ. Coop. Ext. Serv. Fact Sheet 1100.

Noyes, R. T., R. Weinzierl, G. W. Cuperus, and D. E. Maier. 1995. Stored grain management techniques, pp. 71–84. *In* Stored product management. Circular E-912. Oklahoma State University Press, Stillwater.

Reed, C., and J. Harner. 1998a. Cooling of stored wheat in multiple or single cycles using automatic aeration controllers. Appl. Eng. Agric. 14: 497–500.

Reed, C., and J. Harner. 1998b. Thermostatically controlled aeration for insect control in stored hard red winter wheat. Appl. Eng. Agric. 14: 501–505.

Reed, C., J. Harner, and J. Pedersen. 1993. Automatically-controlled aeration in Kansas farm-stored wheat. ASAE Paper 936604. Americal Society of Agricultural Engineers, St. Joseph, MO.

Reed, C. R., V. F. Wright, T. W. Mize, J. R. Pedersen, and J. Brockschmidt-Evans. 1991. Pitfall traps and grain samples as indicators of insects in farm-stored wheat. J. Econ. Entomol. 84: 1381–1387.

SAS Institute. 1987. SAS/STAT user's guide for personal computers. SAS Institute, Cary, NC.

Schmidt, J. L. 1955. Wheat storage research at Hutchinson, Kansas, and Jamestown, North Dakota. U.S. Dep. Agric. Tech. Bull. 1113.

Storey, C. L., R. D. Speirs, and L. S. Henderson. 1979. Insect control in farm stored grain. U.S. Dep. Agric. Farmer's Bull. 2269.

Subramanyam, B. H., D. W. Hagstrum, and P. K. Harein. 1991. Upper and lower temperature thresholds for development of six stored-product beetles, pp. 2029–2037. *In* F. Fleurat-Lessard and P. Ducom [eds.], Proceedings of the Fifth International Working Conference on Stored Product Protection, vol. 3, Bordeaux, France.

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